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Design options for improving protective gloves for industrial assembly work

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ABSTRACT

The study investigated the effects of wearing two new designs of cotton glove on several hand performance capabilities and compared them against the effects of barehanded, single-layered and double cotton glove conditions when working with hand tools (screwdriver and pliers). The new glove designs were based on the findings of subjective hand discomfort assessments for this type of work and aimed to match the glove thickness to the localised pressure and sensitivity in different areas of the hand as well as to provide adequate dexterity for fine manipulative tasks. The results showed that the first prototype glove and the barehanded condition were comparable and provided better dexterity and higher handgrip strength than double thickness gloves. The results support the hypothesis that selective thickness in different areas of the hand could be applied by glove manufacturers to improve the glove design, so that it can protect the hands from the environment and at the same time allow optimal hand performance capabilities.

1. Introduction

In many workplaces it is necessary to protect workers' hands by using gloves. The effects of gloves on different aspects of hand performance capability have been recognised and investigated in a large number of previous studies (Bradley, 1969; Swain et al., 1970; Riley et al., 1985; Bellingar and Slocum, 1993; Imrhan and Farahmand, 1999; Claudon, 2006; Chang and Shih, 2007; Dianat and Haslegrave, 2008). However, unlike studies of hand performance capabilities, very few studies have investigated glove design features. In one of the few attempts, Muralidhar et al. (1999) developed two prototype cotton gloves with the thickness varying between different areas of the hand, based on force distribution and sensitivity patterns on the palmar side of the hand (established from various studies), and compared the effects of wearing the prototype gloves with those of wearing a double glove. One of Muralidhar et al.'s prototype gloves had two and the other four layers of protection in selected hand areas. Although Muralidhar et al. found no significant difference in dexterity between the glove conditions (measured by time to complete a dexterity test), the two prototype gloves were shown to be better than the double glove in terms of handgrip strength.

The primary consideration in designing protective gloves is protection of the hand from injury or discomfort and it is believed that thicker gloves can provide better protection (Muralidhar et al., 1999). In other words, the primary concern when designing gloves has been hand protection rather than hand performance. This policy may be necessary for protection from hazards, but a uniform thickness of material can lead to gloves that are bulky and clumsy to use, perhaps creating other hazardous conditions such as inappropriate grasp on the tool, loss of grip strength or range of motion, or reduced sensory feedback and dexterity. The results of a study conducted by Akbar-Khanzadeh et al. (1995) at an automobile plant revealed that only 42% of workers reported comfort while using their protective gloves and also that, when such protective equipment was inappropriately designed, workers frequently opposed wearing it due to discomfort. As Feeney (1986) pointed out, the possibility of resistance to wearing protective equipment is one of the considerations that should be carefully examined during the design.

There are many design considerations, including material, condition of use, task requirements, comfort and environment, that together with glove manufacturing processes and cost make the

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issue of designing appropriate gloves a complex challenge (Dianat et al., 2012b). Fig. 1 shows a conceptual model of the relationship between design requirements, design considerations/constraints, worker and task. Worker characteristics and design requirements are the inputs to the model, while the design criteria that are generated through the model are the outputs. This model is to develop ergonomic design criteria for evaluation trials rather than a more general model of glove design, and therefore the non-ergonomic parts of design considerations/constraints (i.e. manufacturing process, cost) have been separated out. Glove thickness is obviously an important factor in glove design with its influence on dexterity and tactility, as well as on hand and finger (dis)comfort. Consequently, the material and thickness also have an influence on strength capability of handgrip, pinch grip and forearm torque. Some of the issues that need investigation, among others, are the extent to which gloves cause difficulty in flexing the finger joints and the patterns of discomfort in both barehanded and gloved conditions while working with hand tools. The present study was undertaken for this purpose. Two prototype pairs of gloves were designed and constructed, using the evidence that was currently available from published literature. Their effects on a number of hand performance capabilities were measured and the wearers' subjective assessments were collected. The results with the two prototype gloves were compared with those for bare hand, single-layered glove and double glove conditions. The present study differed from that of Muralidhar et al. (1999) in that the prototype gloves were constructed on the basis of different criteria and also that they were evaluated when performing a work task. The intention was to assist in introducing design alternatives for improving gloves for industrial assembly work. The results of two earlier studies (Dianat et al., 2010, 2012a) which had evaluated the effects of wearing gloves on several aspects of hand performance while working with hand tools (including screwdriver and pliers) showed that the effects of wearing gloves changed over a 2 h work period. So, to have a realistic evaluation of glove effects in a working context, glove evaluation studies need to consider actual working conditions in which gloves are being used by workers.

2. Methodology

There were two phases of work in this study. The first was to develop new designs of gloves and the second was to run an experiment to evaluate the designs.

2.1. Re-design of gloves

The prototype gloves were constructed by modifying a glove that is commercially available and widely used for industrial assembly work, the modification being to the thickness of material so that it could be suited to the hand/tool interaction in particular areas of the hand. The two prototype gloves constructed represented two different approaches. One was based on published evidence of the differences in the areas of discomfort between the bare hand and the gloved hand conditions, and the other was based on the need for finger and hand flexibility while working with tools such as screwdriver and pliers. In other words, the thickness of material was varied over the surface of the hand to reduce the discomfort of wearing gloves or to enhance performance capabilities.

2.1.1. Construction of the gloves

The gloves were made of cotton, the thickness of the basic material (of the commercially available glove) being 0.8 mm. The results of the two previous studies (Dianat et al., 2010, 2012a) had already shown that cotton gloves can be a better option for light assembly tasks than nylon or nitrile gloves (1 mm and 1.4 mm in thickness, respectively), which caused more adverse effects on some hand performance capabilities. Two comparison gloves were included in the evaluation trials: the commercial cotton glove and a double thickness (1.6 mm) cotton glove (one glove worn over another, the two being anchored by strategic stitching). The structures of the two prototype designs are shown in Table 1 and described below. Three sizes of each glove (small, medium and large pairs) were prepared for the evaluation trials.

To modify the cotton glove, the selected areas which would have just the thin layer of material were first mapped on to the glove.

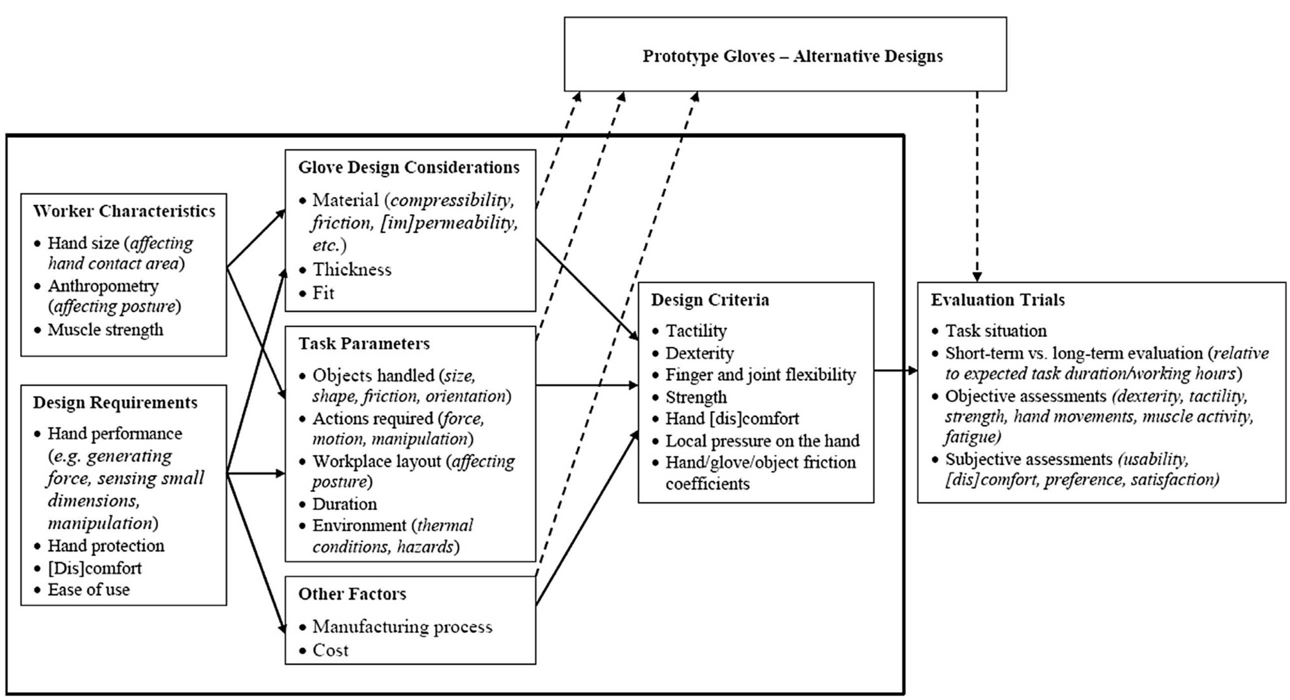

Fig. 1. Conceptual model of the relationship between design requirements, design considerations/constraints, worker and task.

Table 1
The characteristics of the original cotton glove and re-designed gloves used in the study.

Glove type	Material	Appearance[a]	Thickness	Weight of glove (g)
Single-layered	Cotton		0.8	10
Design 1	Cotton		Double – varying over the hand between 0.8 and 1.6 mm	17
Design 2	Cotton		Double – varying over the hand between 0.8 and 1.6 mm	18

[a] The areas outlined for designs 1 and 2 had a single layer.

Then, for each size of glove, a template of the desired areas was prepared from cardboard. The prepared templates were used later as master patterns to cut holes in the "over" gloves to the correct shape.

A pilot test was performed to test whether it would be better to have the glove with the "holes" as the inner glove or as the outer glove. It was thought that, if the edges of the holes caught on the tool or component being manipulated, the glove might deteriorate gradually over the set of evaluation trials or might interfere with the task being performed. Therefore, it was decided that the glove with the "holes" should be the inner glove. This glove with the selected areas removed was placed into another cotton glove of the same size so that it produced a double glove with an unbroken surface for the outer layer.

Another difficulty which had to be overcome when constructing the gloves was to make sure that the inner glove could not slip in relation to the outer glove while it was being used. So the two gloves were sewn together, not only at the edges of the holes but also around the sides of the fingers and around the wrist.

2.1.2. *First glove prototype addressing discomfort areas on the hand*

The first approach to re-designing the cotton gloves was to consider the different patterns of discomfort between the bare hand condition and the gloved hand while working with the hand tools. This data was already available from two previous studies by the present authors (Dianat et al., 2010, 2012a). When gloves are worn, tactility (especially in fingertips) and dexterity will be reduced due to the layer of glove material between the hand and the tool's handle and this is likely to make it more difficult to manipulate both the components and the hand tool. Some gloves used in industry have the fingertips of the gloves removed for just this purpose. Therefore, to have better control over the task and tool, the tool handle should be held firmly between the palm and thenar area, with extra support from thumb and index finger which may lead to more discomfort in these areas of the hand. Several glove characteristics such as thickness, material and flexibility of the material may be responsible for these effects, but it was too complex to consider all the factors simultaneously, so the present experiment was focused on the glove thickness.

The previous studies showed that for the barehanded screwdriver task, the most discomfort was reported in the fingertips of the index and middle fingers. When wearing gloves for this task, the highest levels of discomfort were reported in the palm area, thenar area, and lower part of both the thumb and the index finger (a diagram identifying each of the areas of the hand can be seen in the Appendix). When working barehanded with pliers, the most discomfort was reported in the palm area. When wearing gloves for the pliers task, the highest levels of discomfort were reported in the lower part of both the thumb and the index finger.

The above findings indicate that there is more discomfort when wearing gloves than while barehanded. It was hypothesized that removing material to a single layer may help to reduce (or at least not increase) the gloved discomfort and that the thinner single layer may help to reduce the barehanded fingertip discomfort. Therefore, the re-designed glove incorporated these findings into a glove that had thinner layers in some areas (especially in the region of the fingertips of thumb, index and middle finger), which should facilitate better sensory feedback and dexterity and so minimise slipping or the need for excessive gripping. For practical reasons, the re-designed gloves were constructed of double cotton gloves so that the selected areas with a thinner layer had a single-layered cotton glove. Fig. 2 shows the areas that had a thinner layer in the first re-designed glove and the glove itself is shown within Table 1.

2.1.3. *Second glove prototype addressing difficulty in flexing the fingers and joints*

The second approach to re-design the glove was to consider glove effects that cause difficulty in flexing the finger joints when working with hand tools. A pilot test was performed which

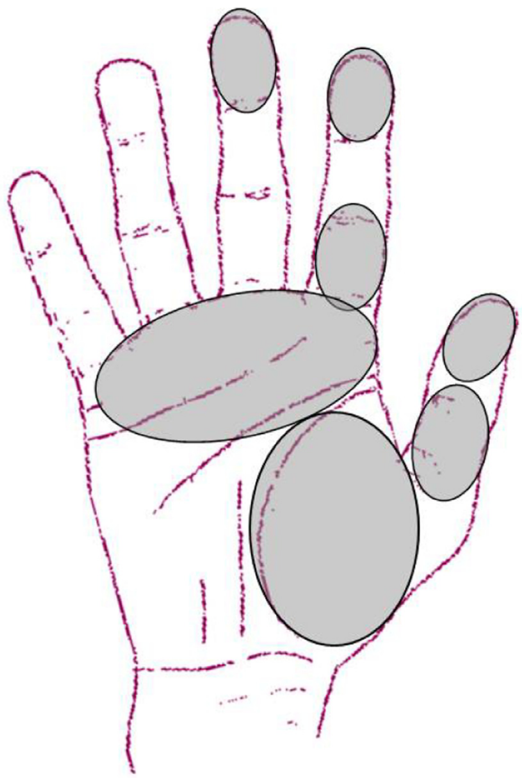

Fig. 2. Areas selected to have a thinner layer in the first re-designed glove (which addressed hand discomfort).

examined this effect and it was found that the primary areas in which resistance was felt during flexion movements of the fingers when manipulating hand tools were at the dorsal aspect of the hand in the metacarpophalangeal and proximal interphalangeal joints (shown as red dashed lines in Fig. 3(a)). It was hypothesized that overcoming the resistance against finger movements at these points may restrict grip posture or necessitate increased force exertion, which in turn could be another possible reason for greater feelings of discomfort when wearing gloves. Therefore, the second re-designed glove had a completely different pattern of cut-outs from Design 1 – the cut-outs of Design 1 are on the palmar side of the glove while the cut-outs of Design 2 are on the dorsal side of the glove. The areas with the thinner layer to reduce the resistance against finger and joint flexion movements are shown in Fig. 3(b) and the glove itself is shown within Table 1.

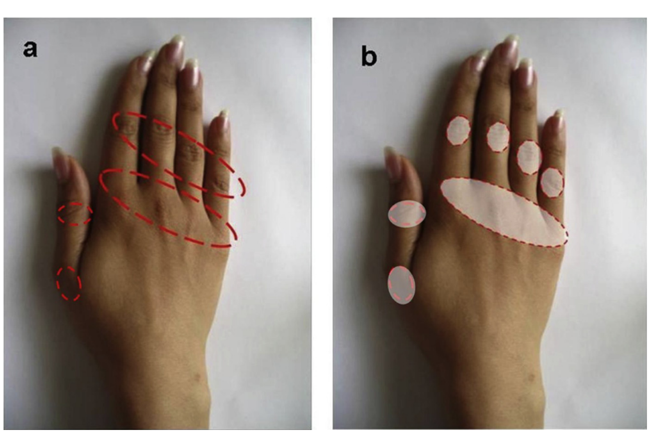

Fig. 3. Second re-design of glove to address difficulty of flexing fingers. (a) Areas where glove may resist finger and joint flexion when working with hand tools. (b) Areas (shown within red dashed lines) selected to have a thinner layer in the second re-designed glove. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Design of evaluation trials

2.2.1. Simulated tasks

For the evaluation trials, participants performed a simulated assembly task using the same experimental equipment and layout as in the previous studies by Dianat et al. (2010, 2012a). The task involved the use of both a screwdriver and pliers, which are two different hand tools commonly used in assembly operations and together demonstrate a range of task demands. The screwdriving task consisted of using a screwdriver to assemble two components together using screws (Fig. 4(a)). The screwdriver had a conventional flat head blade with a longitudinal round cross-sectional handle (having a grooved surface). The handle of the screwdriver was 10 cm in length and 3 cm in diameter and the stem was 100 mm × 6 mm. The screws were 2.5 cm in length with a screw head diameter of 10 mm. The screwdriver task required that each participant fit and support the two components with his left hand, and then turn a screw into each of the component's holes, fastening it with the screwdriver in the right hand. The pliers task was a typical wire tying task using conventional straight type pliers (as frequently used in industry), which had a grip span of 5 cm and weight of 205 g (Fig. 4(b)). The wires were 9 cm in length with a diameter of 1.6 mm. The pliers task required that each participant hold the wire with his left hand and fold both ends of the wire into a U shape using the pliers with the right hand, and then tie the two ends of the U shaped wire together (for one turn).

2.2.2. Experimental trials

The two independent variables examined in the study were (1) hand condition with five levels (single-layered cotton glove, double cotton glove, re-designed glove 1 and re-designed glove 2 as well as barehanded), and (2) point of time within the 2-h duration of the task (with measurements taken at 0, 30, 60, 90 and 120 min). Based on the results of the two earlier studies (Dianat et al., 2010, 2012a) the duration of a 2-h work period appeared to be adequate to evaluate the effects of wearing gloves. Each experimental trial consisted of four 30-min sections of the task (equivalent to a 2-h work period except that short breaks took place at 30 min intervals to permit measurement of the performance measures and recording of subjective assessments). Therefore, a typical trial lasted for a little over 2 h. The participants were asked to work in turn with screwdrivers and pliers, each for 15 min during each 30-min section of the 2-h work period. Four component assemblies or 30 wire ties were completed during each 15 min. Each participant performed five trials (2-h work periods) over five successive weeks, each session testing a different hand condition (with the order of presentation of the hand conditions randomized across the participants). The order in which the two tools (screwdriver and pliers) were used was also randomised across participants within the experimental trials. Performance measures and subjective assessments were taken at intervals over the trial, at the start (0) and then at 30, 60, 90 and 120 min. These were always measured in the same sequence, with the subjective assessments measured prior to the performance measurements to prevent any possible interference. Participants had adequate rest after each 30-min work period while these measurements were recorded, and so it was decided that no further rest periods were required. They were told that they could ask for further rest periods if required, but none did so during the trials. Fig. 5 shows a timeline for the measurements of the different performance

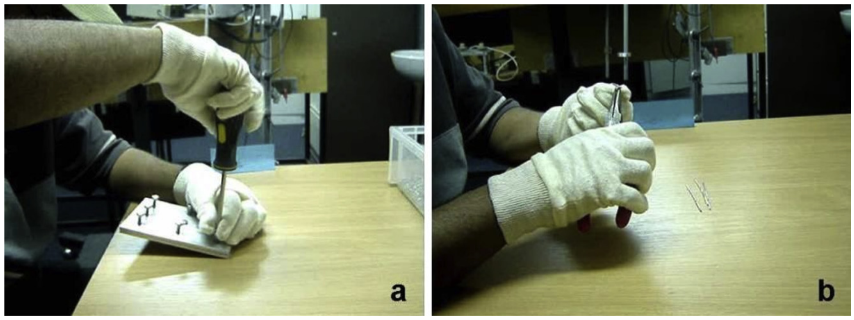

Fig. 4. Working (a) with a screwdriver to assemble two components together using screws and (b) with pliers in a wire tying task.

measures and subjective assessments during each experimental trial.

2.2.3. Measurement of the dependent variables

Since the glove re-designs focused on glove thickness the performance measures of interest were dexterity, tactility and hand strength capability, particularly handgrip, pinch grip and forearm torque. Therefore, the dependent variables measured in the present study were time to complete the pegboard test, number of errors, handgrip strength, pinch strength, forearm torque strength and sensitivity of touch. These measures cover the most important aspects of hand performance/capability required for working with hand tools in assembly tasks. Other performance measures such as muscle activity and wrist posture were not included because only slight effects of cotton gloves on these performance measures had been found in the previous two studies conducted by the authors (Dianat et al., 2010, 2012a). In addition to the performance measures, subjective assessments (rating of ease of manipulation and hand and finger discomfort rating) were recorded during the trials.

The pegboard test, used to measure hand dexterity, is designed to measure gross movements of the hands, fingers and arms as well as finger dexterity, and therefore integrates the speed and precision necessary for assembly tasks (Pennathur et al., 2003; Berger et al., 2009). In this test, the participants were instructed to pick up 30 pegs, one at a time from a pegboard, with their non-dominant hand, pass them to their dominant hand, turn them over and place them in another pegboard. They were asked to complete this task as quickly as possible and the time taken to complete the task was recorded by the experimenter using a digital stopwatch. Number of errors, which was also considered as a measure of dexterity, was defined as the number of objects during each 30-min work period which fell from the hand (i.e. screws, components, wires or hand tools) while performing the simulated assembly task (Dianat et al., 2010).

Handgrip strength, lateral pinch strength and forearm torque strength were three different maximal isometric strength measurements taken during the experiment. The strength measurements followed standard procedures described in the literature. The participants were asked to exert their maximal voluntary strength with their right (dominant) hand and to hold that force for 3 s. Two repetitions of each strength measurement were recorded each time with a 2-min rest break between successive measurements, and the average value of the two trials was used for analysis. The two measurements were considered valid if they were within 10% of each other; otherwise the measurement was repeated (Caldwell et al., 1974; Imrhan and Loo, 1989). Handgrip strength was measured using a hand dynamometer (MKIIIa, made by the Medical Physics Department, Queens Medical Centre, University of Nottingham, UK) with a grip span of 5 cm. This hand dynamometer is based on a bridge of strain gauges and has been used in a number of research studies (Peebles and Norris, 2003; Hillman et al., 2005; Dianat et al., 2012a). Handgrip strength was measured in a sitting posture, with the upper arm next to the trunk, the elbow flexed at approximately 90° and the wrist in a neutral position (Mathiowetz et al., 1985). The lateral pinch strength was measured with a pinch gauge (B&L Engineering, Tustin, CA, USA; range = 0–27 kg). Pinch strength measurements were carried out in a sitting position, with the participant's shoulder flexed forward by about 30°, the upper arm close to the trunk but slightly abducted and the elbow flexed at about 90°, and the wrist in the neutral position (Imrhan and Loo, 1989). A torque-measuring device (including a torque meter, a T-shaped handle and an AFG 500N Mecmesin Advanced Force Gauge) was used for measurement of the forearm torque strength (Dianat et al., 2010, 2012a). The T-shaped handle made an angle of 70° with its shaft to allow a neutral wrist position during the strength measurements. The torque meter was attached to an AFG 500N Mecmesin Advanced Force Gauge (Mecmesin, Slinfold, West Sussex, UK) for recording the torque strength data. Then, the T-shaped handle was attached to the torque meter shaft (mounted on a steel bar), so that the whole apparatus was vertically adjustable to provide the desired height for each participant. Forearm torque strength (in a clockwise direction) was measured in a standing

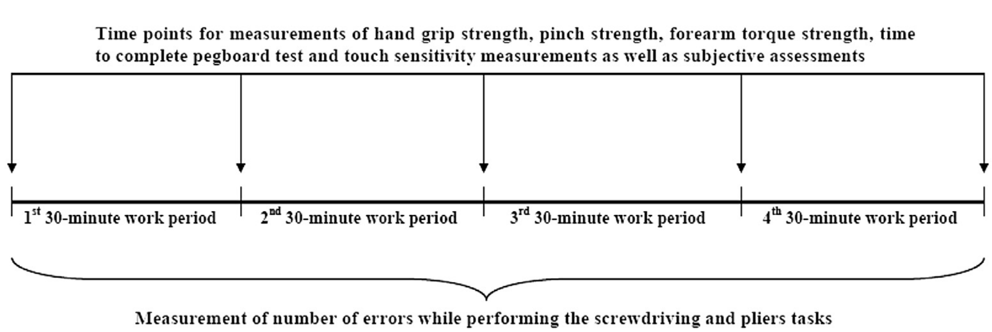

Fig. 5. Timeline for measurement of dependent variables during each experimental trial.

position with the upper arm parallel to the torso, forearm horizontal and elbow flexed at 90° (Caldwell et al., 1974; Mital and Kumar 1998).

Tactile sensitivity was measured by the monofilament test, which has been reported to have good reliability and validity (Jerosch-Herald, 2005). A Semmes–Weinstein monofilament test set (Smith and Nephew Rolyan, Menomane Falls, WI, USA) consisting of 20 nylon testing filaments, all with the same calibrated length of 38 mm but of varying diameters, was used. All measurements (which followed the recommended protocol given by Bell-Krotoski, 1990) were conducted by the same investigator in a quiet room. The participants were asked to turn their head away during the measurements so that they could not see their hand. The participants were instructed to say "touch", when they recognized that they were being touched by a filament. Each filament, in turn, was applied vertically (very slowly) over the selected hand area and slowly moved down until the filament was bent. The filament was maintained in place bowed over for 1.5 s and then slowly removed over 1.5 s. The filaments were presented in both ascending and descending orders of diameter so that the participants could not anticipate the order of presentation. Thus, the touch sensitivity threshold was defined by the smallest filament that could be sensed by the participant.

To investigate the discomfort in different areas of the hand and fingers in more detail a hand map was used, together with a scale of 0–5 (where 0 = No discomfort, 1 = Very low discomfort, 2 = Low discomfort, 3 = Moderate discomfort, 4 = High discomfort and 5 = Extreme discomfort) to measure the severity of the discomfort. The participants were asked to indicate the area of any discomfort that they experienced on the hand map and to rate its severity using the discomfort scale. The responses were then explored in more detail by classifying them into the various areas of the hand and fingers (as defined in the Appendix). In addition, a 5-point scale was used for rating ease of manipulation (where 1 = very easy, 2 = Easy, 3 = Neutral, 4 = Difficult and 5 = Very difficult). The participants were asked to rate their subjective responses on the scales at the start of each trial and thereafter immediately after finishing each 30-min work period during the trial.

2.2.4. Participants

Participants recruited for the experiment were 12 male students from the University of Nottingham, aged between 24 and 34 years (mean age = 30.5 years, SD = 3.2). All participants were right-handed and healthy, with no history of upper limb injury, and none had been professionally involved in working with hand tools (in particular with pliers or screwdrivers). They each signed a consent form before the start of the trials with the option to withdraw at any stage of the study. All participants were paid £8 per hour for their participation. The study was approved by the local ethical review committee at the University of Nottingham.

2.2.5. Data analysis

Statistical analysis of the data was performed with SPSS software version 14.0 (SPSS Inc., Chicago, IL, USA), including summarising descriptive data and mixed model ANOVA for evaluation of the main effects of hand condition and time and of their interaction on the dependent variables. In the mixed model ANOVA, the parameters were estimated using the Restricted Maximal Likelihood (REML) Method and the Covariance structure within time and hand condition groups was selected as Compound Symmetry based on Akaike Information Criteria (AIC). Bonferroni post hoc tests on adjusted means were used to explore the main effects and interactions. The discomfort ratings were analysed using the non-parametric Friedman test. *P*-values < 0.05 were considered statistically significant for all analyses.

3. Results

3.1. Dexterity measures

The main findings of the study are shown in Tables 2 and 3. The results of the ANOVA (given in Table 4) showed a significant main effect of hand condition on both the time to complete the pegboard test ($p < 0.05$) and the number of errors ($p < 0.05$). The post hoc tests indicated that while barehanded or when wearing glove design 1, participants completed the pegboard test faster than when wearing double gloves. In addition, the bare hand condition recorded faster pegboard test completion time than when wearing glove design 2. Wearing glove design 1, single-layered glove, glove design 2 and double glove required 4%, 7%, 10% and 11% higher pegboard completion times, respectively, than the bare hand condition. Furthermore, the number of errors was affected by the type of glove worn, so that more errors were made with double gloves or glove design 2 than while wearing glove design 1. The mean number of errors over a 30-min work period was 0.29 when wearing glove design 1, followed by 0.47, 0.5, 0.66 and 0.73 for single-layered glove, barehanded, glove design 2 and double glove, respectively (as seen in Table 2).

Table 2
Mean (standard deviation) of dependent variables for different hand conditions and over time (number of participants = 12).

Dependent variable	Measures of dexterity		Strength capability		
	Time to complete the pegboard test (s)	Number of errors	Peak handgrip strength (N)	Peak lateral pinch strength (kg)	Peak forearm torque strength (Nm)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Hand condition					
Bare hand	39.3 (5.84)	0.50 (0.41)	43.4 (10.6)	11.3 (1.59)	10.5 (2.68)
Single-layered glove	42.0 (6.83)	0.47 (0.37)	40.2 (8.99)	11.1 (1.37)	10.0 (2.41)
Double glove	43.7 (7.11)	0.73 (0.62)	39.1 (9.82)	11.3 (1.42)	11.8 (3.24)
Glove design 1	40.9 (6.89)	0.29 (0.17)	41.2 (9.87)	11.3 (1.42)	11.1 (3.72)
Glove design 2	43.2 (6.97)	0.66 (0.49)	40.1 (10.1)	11.4 (1.34)	10.8 (3.60)
Time (min)					
0	43.8 (7.78)	N/A	39.6 (9.53)	11.4 (1.43)	10.3 (3.00)
30	43.1 (7.20)	0.76 (0.67)	40.7 (9.67)	11.1 (1.44)	10.7 (3.21)
60	41.3 (6.34)	0.33 (0.21)	41.6 (9.75)	11.2 (1.43)	10.6 (3.27)
90	40.9 (6.68)	0.58 (0.41)	40.8 (9.95)	11.2 (1.45)	10.8 (3.33)
120	40.1 (5.80)	0.45 (0.33)	41.1 (10.94)	11.3 (1.39)	11.0 (3.09)

N/A = not applicable.

Table 3
Mean (SD) of sensitivity of touch (measured in mN of filament force) in various areas of the hand for different hand conditions and over time (number of participants = 12).

	Sensitivity of touch						
	Hand area						
	Thenar	Palm	Hypothenar	Thumb proximal phalanx	Thumb distal phalanx	Index mid/proximal phalanges	Index distal phalanx
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Hand condition							
Bare hand	0.21 (0.02)	0.21 (0.02)	0.21 (0.02)	0.22 (0.03)	0.21 (0.03)	0.22 (0.02)	0.20 (0.05)
Single-layered glove	0.24 (0.02)	0.23 (0.02)	0.23 (0.02)	0.23 (0.02)	0.23 (0.05)	0.24 (0.08)	0.22 (0.01)
Double glove	0.35 (0.22)	0.27 (0.11)	0.29 (0.12)	0.24 (0.02)	0.36 (0.32)	0.36 (0.22)	0.31 (0.20)
Glove design 1	0.25 (0.05)	0.23 (0.02)	0.25 (0.01)	0.22 (0.01)	0.23 (0.02)	0.24 (0.02)	0.23 (0.01)
Glove design 2	0.33 (0.15)	0.29 (0.12)	0.27 (0.09)	0.26 (0.09)	0.29 (0.12)	0.36 (0.17)	0.30 (0.12)
Time (min)							
0	0.27 (0.11)	0.24 (0.06)	0.28 (0.12)	0.24 (0.05)	0.25 (0.09)	0.30 (0.21)	0.26 (0.11)
30	0.27 (0.11)	0.23 (0.02)	0.24 (0.05)	0.23 (0.02)	0.24 (0.08)	0.27 (0.11)	0.24 (0.05)
60	0.28 (0.19)	0.26 (0.10)	0.24 (0.05)	0.23 (0.02)	0.29 (0.25)	0.27 (0.11)	0.26 (0.18)
90	0.27 (0.11)	0.26 (0.10)	0.24 (0.05)	0.23 (0.05)	0.26 (0.11)	0.28 (0.13)	0.25 (0.10)
120	0.28 (0.12)	0.25 (0.09)	0.24 (0.05)	0.23 (0.07)	0.28 (0.20)	0.29 (0.13)	0.25 (0.10)

	Sensitivity of touch					
	Hand area					
	Middle mid/proximal phalanges	Middle distal phalanx	Ring mid/proximal phalanges	Ring distal phalanx	Small mid/proximal phalanges	Small distal phalanx
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Hand condition						
Bare hand	0.21 (0.02)	0.21 (0.02)	0.22 (0.02)	0.21 (0.04)	0.22 (0.01)	0.21 (0.02)
Single-layered glove	0.27 (0.10)	0.23 (0.02)	0.29 (0.11)	0.23 (0.02)	0.31 (0.13)	0.24 (0.05)
Double glove	0.40 (0.24)	0.38 (0.28)	0.60 (0.50)	0.51 (0.40)	0.84 (0.45)	0.51 (0.35)
Glove design 1	0.32 (0.20)	0.23 (0.02)	0.51 (0.32)	0.30 (0.13)	0.74 (0.47)	0.36 (0.22)
Glove design 2	0.42 (0.24)	0.35 (0.22)	0.80 (0.71)	0.045 (0.36)	0.96 (0.72)	0.50 (0.38)
Time (min)						
0	0.36 (0.19)	0.31 (0.21)	0.48 (0.34)	0.30 (0.13)	0.63 (0.41)	0.31 (0.22)
30	0.31 (0.21)	0.30 (0.25)	0.53 (0.42)	0.34 (0.22)	0.57 (0.40)	0.33 (0.22)
60	0.33 (0.22)	0.27 (0.11)	0.50 (0.39)	0.32 (0.21)	0.56 (0.39)	0.35 (0.23)
90	0.30 (0.13)	0.28 (0.13)	0.48 (0.37)	0.37 (0.25)	0.68 (0.54)	0.41 (0.31)
120	0.32 (0.22)	0.27 (0.11)	0.43 (0.29)	0.39 (0.29)	0.65 (0.50)	0.42 (0.32)

Table 4
Summarised results of ANOVA analysis.

Source of variance	Hand condition	Time	Hand condition × time interaction
Time to complete the pegboard test	$p < 0.05$	$p < 0.001$	NS
Number of errors	$p < 0.05$	$p < 0.01$	NS
Peak handgrip strength	$p < 0.001$	$p < 0.05$	NS
Peak lateral pinch strength	NS	NS	NS
Peak forearm torque strength	NS	$p < 0.01$	NS
Sensitivity of touch			
Thenar	$p < 0.001$	NS	NS
Palm	$p < 0.01$	NS	NS
Hypothenar	$p < 0.01$	NS	$p < 0.05$
Thumb proximal phalanx	$p < 0.001$	NS	NS
Thumb distal phalanx	$p < 0.05$	NS	$p < 0.001$
Index mid/pro phalanges	$p < 0.001$	NS	NS
Index distal phalanx	$p < 0.01$	NS	NS
Middle mid/pro phalanges	$p < 0.001$	NS	NS
Middle distal phalanx	$p < 0.001$	NS	NS
Ring mid/pro phalanges	$p < 0.001$	NS	NS
Ring distal phalanx	$p < 0.001$	NS	NS
Small mid/pro phalanges	$p < 0.001$	NS	NS
Small distal phalanx	$p < 0.001$	NS	NS
Rating of ease of manipulation	NS	$p < 0.001$	NS

NS = not significant.

It was also shown that the time to complete the pegboard test ($p < 0.001$) and number of errors ($p < 0.01$) varied significantly over the duration of the task (as shown in Tables 2 and 4), although the number of errors did not change in any systematic way. Time to complete the pegboard test decreased between the start and the end of the task. The time required for completing the pegboard test after 120 min was 8% faster than at time zero.

3.2. Strength measures

The ANOVA showed a significant main effect of hand condition on the handgrip strength ($p < 0.001$) but no significant effect on the forearm torque strength or lateral pinch strength.

A higher level of handgrip strength was recorded while bare-handed compared to when wearing single-layered cotton gloves, double gloves or glove design 2. The post hoc test showed no significant difference between the bare hand and glove design 1, although glove design 1 produced a significantly higher level of handgrip strength than double gloves. Compared to the bare hand condition, grip strength decrements when wearing glove design 1, single-layered glove, glove design 2 and double glove were 4.7%, 7%, 7.2% and 9.5%, respectively.

Regarding the time effect, handgrip strength ($p < 0.05$) and forearm torque strength ($p < 0.01$) changed significantly over the duration of the task, while no significant effect of time was found on the lateral pinch strength. Based on the post hoc tests, handgrip strength at 60 min was higher than that at time zero. Forearm torque strength also increased between the start and the end of the task, in that forearm torque strengths measured at 90 and 120 min were significantly higher than that recorded at time zero. However, these time effects were small in practical terms. Mean handgrip strength only varied between 40 and 42 N over the 2 h work and forearm torque strength between 10.3 and 11.0 Nm.

3.3. Touch sensitivity

As shown in Table 3, touch sensitivity in all the hand areas was greatest while barehanded (that, it had lowest filament force threshold in mN) compared to when wearing gloves. In all hand areas, sensitivity of touch thresholds while barehanded was found to be significantly different from those when wearing any of the gloves. Gloves reduced touch sensitivity in both small and ring fingers (ring mid/proximal phalanges, ring distal phalanx, small mid/proximal phalanges and small distal phalanx areas) more than in the other hand areas. Touch sensitivity thresholds in the thinner areas of glove design 1 were similar to those thresholds when wearing a single-layered cotton glove. No significant difference was found between glove design 2 and double gloves in any of the hand areas. In contrast, significant differences were found in the sensitivity thresholds between single-layered cotton gloves and glove design 2 in all hand areas.

No significant effect of time was found on touch sensitivity. However, a significant interaction effect was found between hand condition and task time for the touch sensitivity of the thumb distal phalanx and hypothenar area. For the hypothenar area, wearing double gloves and glove design 2 caused more sensitivity decrement at the start of the task than at other times, whereas touch sensitivity did not change over time while barehanded or when wearing single-layered gloves or glove design 1.

3.4. Subjective measures

None of the subjective assessments (i.e. the rating of ease of manipulation and hand and finger discomfort rating) were found to differ significantly between the hand conditions. The participants rated ease of manipulation as between “very easy” and “easy” for all hand conditions, with lowest and highest mean ratings recorded for the bare hand (mean $= 1.4$; SD $= 1.08$) and double gloves (mean $= 1.9$; SD $= 1.20$), respectively. Also, relatively similar levels of discomfort, that was between “very low” and “low”, was recorded for all hand areas when performing the simulated tasks with both hand tools. Subjective assessment of the ease of manipulation did change over the duration of the task ($p < 0.001$), so that better ratings of ease of manipulation were given at the start of the task compared to later. At the beginning of the task, participants rated the task as “very easy” with a mean rating score of 0.7 (SD $= 0.68$), compared to as “easy” with a mean rating score of 2 (SD $= 1.05$) after 120 min.

4. Discussion

The present study investigated the effect of the two modified designs of glove on a number of hand performance capabilities and subjective assessments and also compared their performances against those with bare hand, single-layered cotton glove and double cotton glove while working with pliers and a screwdriver. The two re-designed gloves (e.g. ‘glove design 1’ and ‘glove design 2) were produced from cotton gloves and were based on subjective hand discomfort assessments so that the thickness could be suited to particular areas of the hand (i.e. had thinner layers in some areas). It was hypothesised that manipulation of the glove thickness would improve task performance or maintenance of performance over the duration of a task. The results of the evaluation trials indicated that some of the performance and strength capabilities of the hand with glove design 1 were comparable to that recorded with the bare hand condition, while no improvements were found in the hand performance capabilities when wearing glove design 2 compared to other conditions.

One of the main findings of the study was that some improvements were found in dexterity with glove design 1. The results of the study indicated that the bare hand condition and glove design 1 produced shorter pegboard completion times (which means better dexterity) than double gloves. In contrast, glove design 2 required more time to complete the pegboard test than the bare hand condition. The number of errors, which was considered as another measure of hand dexterity while performing the experimental tasks, also improved with glove design 1 in comparison to double gloves or glove design 2. These findings suggest that the first prototype glove improved dexterity compared to the double glove condition, whilst the second prototype glove showed no improvement in this respect. According to these findings for glove design 1, it seems that the improvement of tactility (especially in fingertips) and dexterity is perhaps a more important consideration in glove design than improved finger and joint flexibility which was provided by the design of the second prototype glove. Therefore, in terms of hand dexterity, glove design 1 along with the bare hand or single-layered cotton gloves appear to be a better choice than double gloves or glove design 2 for a task that requires fine manipulation while working with hand tools such as screwdrivers and pliers. These findings would need to be validated in workplace settings but provide a unique insight into the performance issues underpinning the use of gloves for manual tasks.

Significant differences were found between handgrip strength measurements, although neither pinch strength nor forearm torque strength values were affected by gloves. The greatest handgrip strength was recorded while barehanded, whereas double gloves produced the lowest recorded strength. This finding suggests that greater grip strength decrement seems to be expected when wearing thicker (double) gloves. This result is in agreement with findings from other studies (Chang and Shih, 2007; Muralidhar et al., 1999; Dianat et al., 2012a), which have shown grip strength decrements when wearing gloves. Again, these findings provide a basis for informing the use of gloves in the workplace but would need further validation for specific contexts of use.

It is also interesting to note that higher handgrip strength values were recorded with the bare hand and glove design 1 compared to when wearing double gloves. A higher level of handgrip strength was also produced with the bare hand condition than with glove design 2, whereas no significant difference was found between the bare hand and glove design 1 in this respect. Thus, compared to the bare hand condition, higher strength decrement seems to be expected when wearing glove design 2 than glove design 1. Therefore, it appears that between the re-designed gloves, only glove design 1 permitted higher handgrip strength than double gloves, which can be considered as an advantage for the first prototype glove over double gloves for workplace tasks that require handgrip strength while working with hand tools. Perhaps, better grip strength with glove design 1 can be attributed to the better fit between the hand and the tool’s handle. Therefore, simply in terms of handgrip strength, the bare hand condition or glove design 1 seems to be a better option than single-layered glove, double glove or glove design 2 for a task involving the gripping and use of hand tools such pliers or screwdrivers. However, in terms of pinch strength or forearm torque strength, there is no preference between gloves and no strength decrement or improvement can be expected with re-designed gloves while working with hand tools.

As shown by the results of this study, touch sensitivity in terms of filament force threshold (mN) for all the different hand areas examined in the study was greatest while barehanded compared to when wearing gloves. This supports the findings of previous studies (Shih et al., 2001; Tiefenthaler et al., 2006; Dianat et al., 2010, 2012a) which have reported touch sensitivity decrements due to gloves. It was also shown that gloves had more of an adverse effect on the touch sensitivity of the small and ring fingers and increased touch sensitivity thresholds in these two fingers more than in the other hand areas. This could indicate a key consideration in designing gloves for use in tasks where fine motor tasks are required or the specific sensitivity of these fingers is a key feature of the task (e.g. picking up small components). The results suggest that touch sensitivity in most areas of the hand was less affected by single-layered gloves or glove design 1 than with double gloves or glove design 2, which is not surprising as both double gloves and glove design 2 had two layers at the palm side of the hand. The improved touch sensitivity with glove design 1 may be explained by thinner areas at the palm side of the hand that provide better tactile feedback than double gloves or glove design 2. Therefore, the results suggest that the bare hand condition, single-layered cotton or glove design 1 serve better for a task that involves tactile feedback and fine manipulation of the task, while double gloves or glove design 2 are not suitable options in this respect.

The development of guidelines regarding glove design features in this study was based on a new design of cotton gloves with emphasis on glove thickness as one of the design properties. In addition, the participants in the current study were relatively young, healthy and non-professional workers who spent 2 h assessing each glove condition in controlled laboratory conditions. The working environment in real assembly operations could be different as some glove materials, particularly cotton, may tend to stretch and wear over time and may also be influenced by moisture from sweat and the environment. Moreover, repetitive use of the gloves may lead to skin problems such as irritation, blisters and calluses, which were not apparent in the short-term trials that were conducted. Therefore, more detailed studies using different glove materials, thicknesses, hand tools and tasks are required to fully validate the effectiveness of the proposed design in real workplaces. Moreover, since hand performance has been less considered in glove designs, it is therefore necessary to take into account designs that protect the hands from the environment but at the same time allow optimum hand performance capabilities. To take account of this, hand performance capabilities in each task should be evaluated by both objective and subjective (i.e. preference, comfort, satisfaction, usability, etc.) assessments and designs should be based on improving the hand performance capabilities. Obviously, there are different ways that protective gloves could be designed (i.e. based on minimising local force pressure on the hand, improving grip patterns or friction between the glove and gripping surface, etc.) and therefore, further studies testing other design possibilities based on hand performance capabilities are recommended. However, the findings reported in this paper represent a key stage in verifying which designs show particular advantages in the use of hand tools which then provide a basis for further research in specific workplaces.

5. Conclusions

Two prototype gloves were produced from cotton gloves based on the findings of subjective hand discomfort assessments for industrial assembly work and aimed to match the glove thickness to the localised pressure, sensitivity and flexibility in different areas of the hand. It was shown that the performance or strength capabilities of the hand with glove design 1 were comparable to that observed with the bare hand condition, so that both produced lower pegboard completion times (i.e. increased dexterity) than double gloves, and there was a lower number of errors with glove design 1 than with double gloves. Also, glove design 1 and the bare hand condition produced higher handgrip strength values compared to double gloves. Lateral pinch and forearm torque strength capabilities were not affected when wearing any of the gloves in this experiment. It appears that improved dexterity and tactile feedback in some areas of the hand with the first prototype glove tended to give more improvements in performance and strength capabilities of the hand than with the second prototype glove. The findings support the hypothesis that selective variation in thickness over some areas of the hand can be applied to improve industrial glove design. Such an approach is particularly useful for gloves intended to protect the hands from the environment while at the same time allowing better hand performance capabilities. The findings present a unique insight into the design of gloves for industrial hand tool use but further research is needed to validate the findings in real workplaces, looking at wider factors and local work practices.

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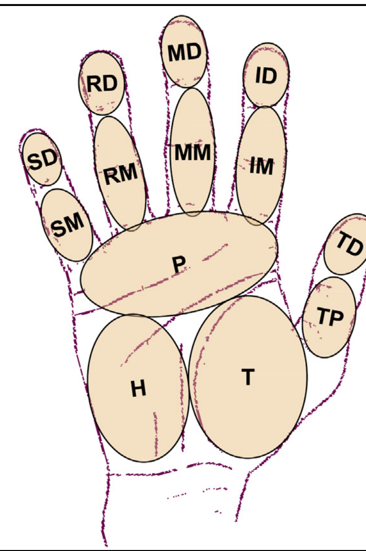
Appendix

Hand map and definition of areas of the hand and fingers for the subjective assessments.

T	Thenar area
P	Palm area
H	Hypothenar area
TP	Thumb proximal phalanx
TD	Thumb distal phalanx
IM	Index finger middle and proximal phalanges
ID	Index finger distal phalanx
MM	Middle finger middle and proximal phalanges
MD	Middle finger distal phalanx
RM	Ring finger middle and proximal phalanges
RD	Ring finger distal phalanx
SM	Small finger middle and proximal phalanges
SD	Small finger distal phalanx



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